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FOREIGN TECHNOLOGY DIVISION

"THE EFFECT OF TURBULENCE PARAMETERS ON THE TRANSFER OF HEAT BY FLOW AROUND A SPHERE"

By

Czeslaw Strumillo, Adam Markowski, Stefan Grabowski

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"The Effect of Turbulence Parameters on the Transfer of Heat by Flow Around a Sphere" by Czeslaw Strumillo, Adam Markowski, and Stefan Grabowski

Chemical Engineering Istitute of Lodz Polytechnical

Submitted January 25, 1975.

Polish, Russian, and English Abstracts

Praca niniejsza dotyczy wpływu parametrów burzliwości na ruch ciepła przy opływie kuli. Doświadczenia wykonano przy użyciu kul metalowych o średnicach 59,6 i 41,4 mm, ogrzewanych od wewnątrz. Liczbę Reynoldsa zmieniano w zakresie $3\cdot10^3$-$3\cdot10^4$, natomiast zakres zmian parametrów burzliwości wynosił: stopień burzliwości ε — od 3 do 24% i bezwymiarowa skala burzliwości L_g/d — od 0,07 do 0,75. W wyniku interpretacji danych doświadczalnych stwierdzono przydatność dla ciał osiowo-symetrycznych simpleksu β zaproponowanego dla przepływu w rurze przez Mościcką [9]. Analiza statystyczna otrzymanych wyników pozwoliła na otrzymanie następującej zależności dla średnich współczynników wnikania ciepła:

$$Nu = 0{,}142\, Re^{0,60} Pr^{0,33} (\beta_d)^{-0,16}.$$

Работа касается влияния параметров турбулентности на теплоперенос при обтекании шара. Опыты проведены при использовании металлических шаров диаметром 59,6 и 41,4 мм, с внутренним обогревом. Число Рейнольдса изменяли в интервале $3\cdot10^3$-$3\cdot10^3$, а пределы изменений параметров турбулентности были равны: степень турбулентности ε = 3-24% и безмерный масштаб турбулентности L_g/d = 0,07-0,75. В результате интерпретации экспериментальных данных обнаружена пригодность для осевосимметрических тел симплекса β, предложенного Мосьцицкой [9] для течения в трубе. Статистический анализ полученных результатов позволил получить следующую зависимость для средних коэффициентов теплоотдачи:

$$Nu = 0{,}142\, Re^{0,60} Pr^{0,33} (\beta_d)^{-0,16}.$$

The work deals with the influence of the turbulent parameters on heat transfer coefficients by flow of air stream past single sphere.

The inside heated metallic spheres of 59,6 and 41,4 mm diameter placed in a vertical wind tunel were used. The variable parametres varied as follows: Reynolds number: Re = $3\cdot10^3$-$3\cdot10^4$, level of turbulence: ε = 3-24%, dimensionless scale of turbulence: L_g/d = 0,07-0,75.

It was found that number β proposed by Mościcka [9] for flow in the pipe, is suitable for the correlation of heat transfer data for the sphere.

On the basis of the statistical analysis the results of the experiments were correlated by the dimensionless equation:

$$Nu = 0{,}142\, Re^{0,60} Pr^{0,33} (\beta_d)^{-0,16}.$$

Introduction

The transfer of heat and mass from spherical particles to a stream of liquid appears in many industrial problems. We can here number the processes of the dispersive drying up of solid bodies, the moistening of the air, the chemical processes occuring in catalytic layers, the problems of spherical exchanges of heat as well as of dissolution, sublimation and barbotage.

In a majority of the applica tions mentioned here, we have to deal with turbulent flow. In these conditions one of the most useful methods of intensifying the transfer of heat and mass is the artificial increase of turbulence of a liquid flow. This is realized through the introduction to the flowing liquid of a different kind of turbulence generators which induce a change in the parameters determining the core turbulence. This is confirmed in many of the works devoted to this problem [1-5].

The development of measuring techniques, especially thermoanemometry [6,7] allowed for an accurate determination of the parameters of core turbulence. The obtaining of correlation equations of heat and mass transfer was made possible in these cases by an artificially increased turbulence. Analysis of the experiments permit confirmation of the divergence between the various authors' results. An additional inference resulting from analysis of the literature is the confirmation of the need for the resolution of this problem on the theoretical level.

In light of these considerations it appears that the appropriate conduct of further experimental work, having the goal of explanation of the mentioned differences, and at the same time the acquisition of generalized methods calculated for

this process should take place.

The object of the present work was the experimental determination of the influence of the basic parameters describing the isotropic fields of liquid flow trubulence, that is to say, the degrees and scale of turbulence in heat transfer from a single metallic sphere located in an air stream.

The Current State of the Problem

The transfer of heat and mass during flow around a body is strictly connected to the hydrodynamic conditions of a flowing liquid. These conditions are usually defined by Reynolds numbers. For a stratified flow the determination of the Reynolds number by use of the velocity of the liquid flow allows the synonymous determination of the hydrodynamic conditions of flow. It is not sufficient in the area of turbulent motion, where we have to deal with a continual change of values and the direction of the vector of velocity. The speed of the liquid's flow refers to that averaged over time.

For these conditions a Reynolds number is not a sufficient criterion of hydrodynmaic similarity, and it is necessary for the completion of this description tha t we have the aid of interdependent parameters of turbulence: the degree and scale of turbulence. This fact is confirmed in the works of Hinze [8], Moscicki [9], as well as by Boulous and others [10].

Consideration of these parameters allows the obtaining of various hydrodynamic conditions, and at the same time of various intensities of exchange processes by the same Reynolds number.

The problem presented until this time was not subject to full theoretical solution. This results mainly from the lack of

an accurate theory of turbulence, and particularly the difficulty of defining the phenomenon of turbulent exchange momentum, of heat and mass in the boundary layer. This is connected to the indefinite knowledge of the parameters of turbulent transfer: turbulent viscosity, turbulent conductivity and turbulent diffusion, which are necessary for the solution of the generalized differential equations describing this process. The parameters are not functions of the state and depend upon the situation. One of the most direct methods of determining these parameters is based on knowledge of the velocity distribution as well as the Prandtl concept, until this time the mixing length. Other methods described are in the works of McEligot [11] and Bankston [12].

The solutions mentioned were obtained for a fluid flow in a pipe or for the flow around two-dimensional plates, where the velocity distribution is accurately described. This problem is remarkably complicated in the case of flow around rotary bodies,i.e., a sphere or a cylinder, where we have to deal with the mixed character of the movement and with the phenomenon of the separation of the boundary layer. For these conditions there was not obtained thus far a complete theoretical solution of differenctial equations and recently the published work of Galloway [13] concerns only the fron-half of a sphere. This author as a result of the numerical solution of differential equations describing the motion of heat in the flow around a sphere, using the mentioned conception of centrifugal viscosity based on the Prandtl-defined mixing length, obtained the following relationship

$$Fs = 1{,}47(1 - A_2\xi^2 - A_4\xi^4)\frac{1}{1+\Phi_2(Pr)}, \tag{1}$$

~~gdzie~~ where

$$Fs = \frac{Nu - 2}{Re^{0.5}\,Pr^{0.33}}, \tag{2}$$

$$\Phi_2(Pr) = \frac{0{,}0840}{Pr^{0.33}} - \frac{0{,}0079}{Pr^{0.67}} + \frac{0{,}001325}{Pr} - \frac{0{,}00406}{Pr^{1.33}} + \frac{0{,}00317}{Pr^{1.67}}, \tag{3}$$

$$\zeta = \int_0^x \left[\frac{U_1(x)}{U_\infty}\right]\left[\frac{r(x)}{d}\right]^{2k} d\left(\frac{x}{d}\right) \tag{4}$$

(for flow around a sphere k = 1).

A comparison of the derived solution with the experimental results indicate its utility only for low ranges of turbulence degrees. This connected to the imperfection of the turbulence model based on the Prandtl concept as well as with the simplified description of the velocity profile of Ruckenstein and Berbente [14] used in this work. There appears to be an appropriate reception in this area of the modified conception of Deissler, Van Driest or others [11, 12]

Great difficulties in the analytic description of heat transfer in conditions of turbulent flow caused the need for the undertaking of a series of experimental works. From the analysis of these works [15,16] it results that bodies flowed around (spheres, cylinders)the intensifica tion of heat transfer by an increase of turbulence of the inflowing system is connected with the appearance on the boundary layer of the following phenomena:

1. A later passing from a laminar to a turbulent boundary layer (by lower angles of substitution).
2. Interactions of the vortices of the main stream on the flow in the laminar and turbulent boundary layer.
3. Displacements of the point of separation and development of changes in the track behind the body discussed.

Quantitative analysis regarding the evaluation of

the influence of separate effects on the intensification of the exchange processes is not possible at the moment.

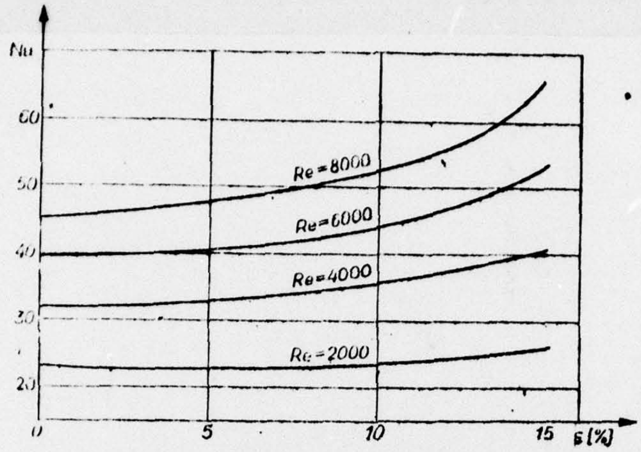
The principal criterial equation used by various authors, defining the movement of heat in flows around a body and accounting for the parameters of trubulence is the relationship

$$Nu = f\left(Re,\ Pr, \varepsilon, \frac{L}{d} \right), \tag{5}$$

where ε — degree of turbulence, L/d — simplex formulating the relation of the scale of turbulence to a linear dimension.

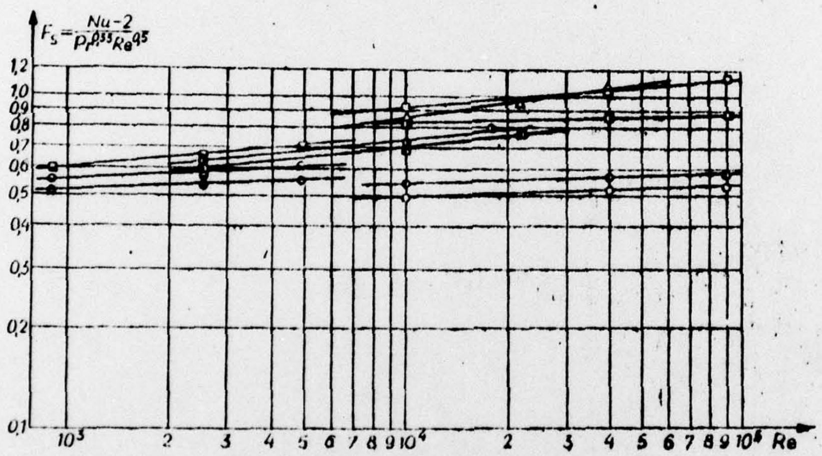
A significant number of the authors [17,18,19] restrict their investigations solely to the effect of the degree of turbulence adding the assumption that the effect of the scale of turbulence is insignificant. Such data are represented appropriately in figure 1, where there are represented the results of Venezjan's work [20]. There is observed an increase in the intensifica tion of heat transfer Nu at approximately 50% in the result of the increase ε from 2 to 15% as well as the relationship of this increase upon the Reynolds number range.

Another group of authors [9, 21, 22] account in their work as well for the scale of turbulence, however their views on the effect of this parameter are contradictory. One can observe as well great differences vis-a-vis the definition of the size of the effect of the degree of core turbulence on the intensity of heat transfer. This is shown in figure 2 where the results of various experimental works are shown, The nonuniform opinions pertain as well to the influence exerted by core turbulence on the front-half as well as the back-half of a sphere, and also the effect of the degree of turbulence in the area of lower and higher values of this parameter [21,22,25]. A certain test of the interpretation of these divergences is given in work [9].



Rys. 1. Zależność $Nu = f(\varepsilon)$ wg [20]

Fig. 1. Relationship $Nu = f(\varepsilon)$ after [20]



Rys. 2. Zależność $Fs = f(Re)$

Fig. 2. Relationship $Fs = f(Re)$

- ◑ – Brown [23], ε – 10%, d – 12,7 mm,
- ◐ – Cary [24], ε – 1,3%, d – 127 mm,
- ⊖ – Galloway, Sage [24], ε – 5%, d – 25,4 mm,
- ◒ – Galloway, Sage [24], ε – 10%, d – 25,4 mm,
- ▭ – –„– –„– [24], ε – 15%, d – 25,4 mm,
- ○ – Hsu [25], ε – 1,3%, d – 1,78 mm,
- ◧ – Short [25], ε – 10%, d – 12,7 mm,
- △ – Venezian [20], ε – 10%, d – 25,4 mm,
- ▣ – Wadsworth [24], ε – 1%, d – 101,6 mm,
- □ – –„– [24], ε – 5%, d – 101,6 mm

The current state of the problem as stated indicates that there is a lack of accurate, certain analytic methods, permitting a definition of the effect of core turbulence on the intensity of heat transfer from axial-symmetrical bodies (sphere, cylinder). Numerous experimental undertakings conclude with contradictory opinions via-a-vis the quantitative grasp of the process considered. They indicated as well the great possibilities of an intensification of these processes by the application of artificial promoters of turbulence.

Experimental Portion

Experimental tests took place in a vertical wind tunnel of the closed type at an altitude of 7 m, and with an internal diameter of 228 mm. The neasuring section was positioned at the upper part of the tunnel, in which there was installed a test sphere. The intensity of the air flow was measured by the use of a Prandtl pipe connected with an inclined manometer.

Metallic spheres were used for the test with diameters of 59.6mm and 41.4mm. They were fabricated from copper sheeting, and then, after the installation of thermal elements on its surface as well as on the heating coil, the interior of the spheres were executed in fluid zinc. Liquid was supplied to the coil from a pump at a regula ted rate. The amount of the flowing liquid was recorded and the temperature at the intake and outlet of the coil which permitted the achievement of a balance of heat, and then a determination of the coefficient of heat penetration. Tests accounted for the following range of parameter changes:

- Reynolds number = $3 \cdot 10^3 - 30 \cdot 10^3$,
- degree of turbulence $\varepsilon = 3 - 24\%$
- scale of turbulence expressed in the form of simplex L/d = 0.07 - 0.75

The special construction of the research apparatus as well as construction of the spheres are represented in work [26].

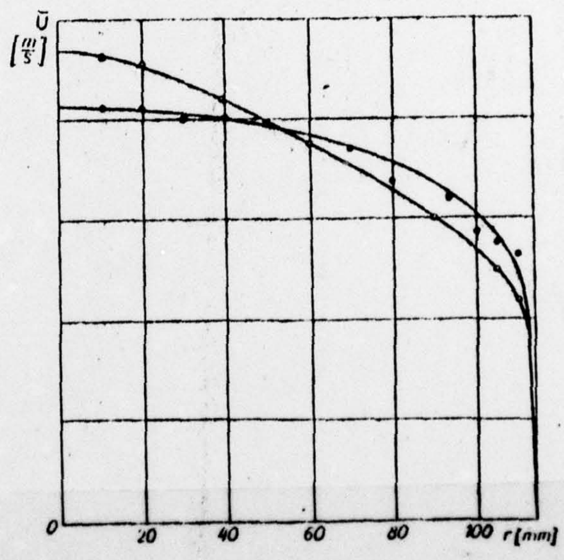
As the promoters of turbulence there are used perforated plates as well as woven nets from ferrous bronze wire. Such a solution has assured the finding of a wide range of variations of turbulence parameters. Some structural parameters of several turbulence promoters are compared in Table 1.

Measurement of the turbulence parameters of the airstream flow was obtained with the aid of the constant temperature thermometric DISA D 01. Employed for the measurements were sensors of the heating wire type 55 E 20. The gradation of these sensors were provided in the aerodynamic tunnel DISA 55 D 41/42. The shift of the sensors to the radius of the tunnel was accomplished with the aid of the shifting system DISA 55 E 40 with an accuracy of 0.1mm. The measures of the trubulence parameters as well as the determined dimensions of the heat transfer were provided in separate time intervals with the aim of avoiding the deformation of the boundary layer developed by the presence of the sensor. In the result of the tests there was used a velocity distribution in a section of the tunnel (figure 3), which was used for the determination of the average speed. A comparison in this way of the results obtained with the indica tors of the Prandtl pipe demonstrate a deviation not exceeding 4%. Moreover, analysis of the obtained velocity profiles without a net and in its presence (figure 3) point to a deformation of the velocity profiles obtained by a net. Hence, the corollary resutls that with the aim of enabling the comparability of results, the Reynolds number should be defined by the use of volumetric velocity, which was used in the present work.

The degree of airstream trubulence defined by the described method in works [8,27], and the dimension of the integral

Tabela 1 – Table 1

Lp. No.	Rodzaj promotora King of promoter	Materiał Material	Grubość blachy Plate thickness	Średnica otworów Hole diameter [mm]	Podziałka otworów Hole pitch [mm]	Ilość otworów Hole number	Stopień zajęcia powierzchni przekroju Degree of filling of cross-sectional area
1	Płyta perforowana perforated plate	aluminium	5	14	17	127	0,485
2		stal steel	10	13	19	109	0,619
3	Siatka tkana o kwadratowych oczkach Woven net with square mesh	żelazobrąz ferrobrons	średnica drutu wire diameter $d = 1$ mm			$\frac{\text{liczba oczek}}{\text{cm}^2} = 4$ $\frac{\text{mesh number}}{\text{sq}\cdot\text{cm}} = 4$	



Rys. 3. Rozkład prędkości w sekcji pomiarowej

Fig. 3. Velocity distribution in the measuring section

○ – bez siatki, ● – siatka nr 1, Re = 22000

o - without a net,
● - net nr 1, Re = 22000

scale of turbulence was calculated by the graphic method (figure 4) in the manner presented in works [8,9]. As a result of the analysis of the obtained measurement results, the values ε and L_g depend on the geometry of the turbulence promoters used. Another corollary emerging from these tests is confirmation that with an increase of a sphere's distance from a promoter of turbulence the degree of turbulence diminishes as well as does not undergo changes due to changes in the airstream flow. A similar confirmation can be found in works [3,29].

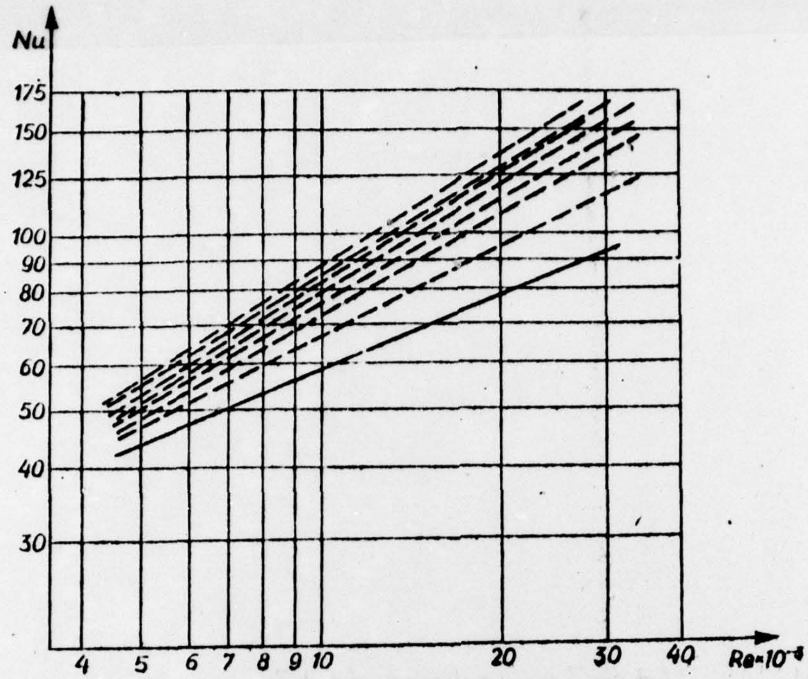
Interpretation of the Results

The initial point of interpretation of the experimental results was the determination of the relationship of the Nusselt number to the Reynolds number. Such data is represented in figure 5. Analysis of the graph indicates that the measurement points were arranged on several straight lines at close values of the directivity coefficient but at other constants. Each of the represented relationships correspond to a different value of the airstream turbulence parameters. With an increase in flow turbulence defined equally as the degree of turbulence ε, and as in the scale of turbulence L_g/d, the heat transfer rises until the maximum effect of intensification reaches approximately 60%. From this graph one can observe as well that this effect is greater for the higher range of Reynolds numbers.

Rys. 4. Zależność $g(r) - f(r)$

Fig. 4. Relationship $g(r) - f(r)$

◐ - net nr 1, ◑ - net nr 2, o - net nr 3, Re = 20000



Rys. 5. Zależność $Nu = f(Re)$

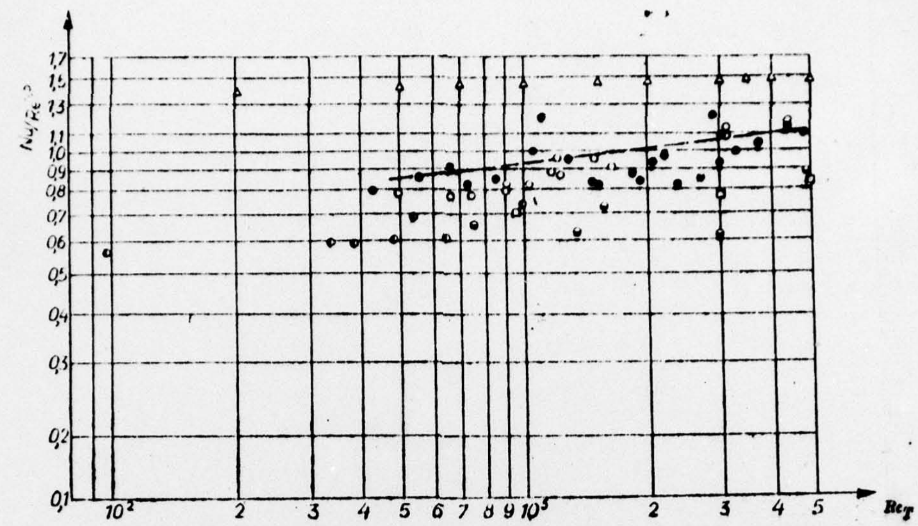
Fig. 5. Relationship $Nu = f(Re)$

- - - w obecności promotorów burzliwości, ——— bez promotorów burzliwości

--- in the presence of turbulence parameters,
——— without turbulence parameters

Similar results to this effect are here mentioned in the turbulence parameters used by Lavender and Pei [19], Venezjan et al [20] as well as Galloway and Sage [24]. Higher values of heat transfer intensification (over 70%) were confirmed by Endoh et al [22], and lower (approx. 40%) by Isatajew and Zanawajew [17].

Because many of the authors interpret the results of their tests with the aid of the introduction for general criterial equation of the Reynolds turbulence number Re_T, their own results were converted similarly and in this way were used in the graph represented in figure 6. One should remark here upon a certain spread of experimental points which results from the disregard in this type of interpretation of the effect of the scale of turbulence. Additionally, in this figure there are included the data used by other authors. In this sense one can acknowledge the position of one's own data with satisfaction.



Rys. 6. Wpływ burzliwej liczby Reynoldsa Re_T na ruch ciepła przy opływie kuli
Fig. 6. Effect of the turbulent Reynolds number Re_T on heat transfer at the flow past a sphere

● – our tests, ◒ – wg Galloway, Sage [24], ◑ – wg Galloway, Sage [30], ○ – Lavender [19], □ – Bieszczjutko [31], △ – Gostkowski [25]

Further quantitative analysis of the experimental results obtained are carried out on the basis formulated by Moscicka [9] of the hydrodynamic criteria of similarity of turbulent flow fields in a pipe. From the equations put forth in this work, there results that the degree and scale of turbulence cannot be treated as independent hydrodynamic criteria defining the core turbulence. For one cannot experimentally separate their effect on the intensity of the processes of heat transfer and mass. Also, an authoress proposed the introduction to the general criterial equation of heat transfer or mass a simplex tying both the mentioned parameters, so defined as

$$\beta_R = \frac{L_g}{R}\,\varepsilon^2 \qquad (6)$$

Because in the present work the aim of test was heat transfer about a sphere there necessarily appears the consideration in simplex definition (6) of a characteristic dimension, such as is the diameter of the sphere [28] instead of the radius of the research tunnel. This fact has equally confirmation in a number of the experimental works currently under discussion.

Considering the remark above, we obtain the following criterial equation of heat transfer:

$$Nu = f(Re, Pr, \beta d). \qquad (7)$$

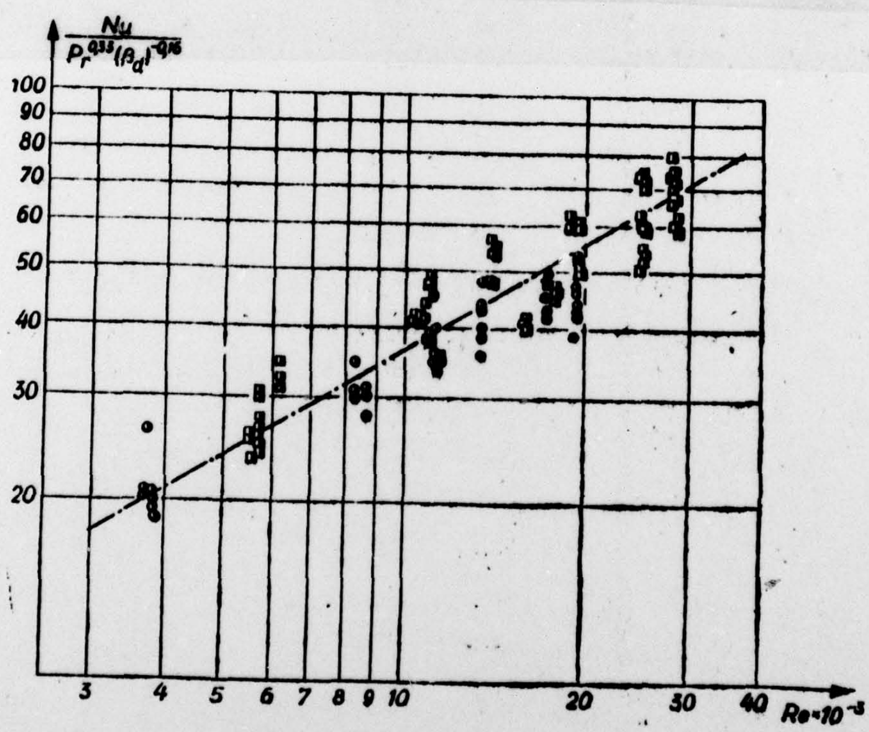
Utilization of equation (7) for interpreting the experimental results with the aid of methods of statistical analysis (Gauss multiplier method [29] is accomplished on the digital computer ODRA 1204) allowed for use the following correlation equation:

$$Nu = 0.142 Re^{0.6} Pr^{0.33} (\beta d)^{-0.16}. \qquad (8)$$

The corresponding statistical parameters amount to:

$$R_y = 0.954, \ \beta_y = 0.046, \ D_y^2 = 0.0098.$$

A graphic illustration of equation (8) is given in figure 7.



Rys. 7. Zależność } $\frac{Nu}{Pr^{0.33}(\beta_d)^{-0.16}} = f(Re)$
Fig. 7. Relationship }

○ – d = 61.6 mm, ▯ – d = 50.0 mm

In the obtained equation (8) the Nusselt number depends on the non-dimensional simplex β_d to the power (-0.16). For flow bodies which have not used a parameter of this type, immediately for a heat exchange during flow through a pipe, Moscicka [9] obtained the equation

$$Nu = 0.005Re^{0.8}Pr^{0.33}(\beta_R)^{-0.25}. \qquad (9)$$

Differences of indexes for simplexes expressing the turbulence of a flow can result here from the distinct geometry of systems.

In equation (8) the index according to the Reynolds number amounts to 0.6. This value appears to be completely explained in light of the work of Rowe and Claxton [32], which discusses for a similar range the number Re given in work [26].

Corollaries

1. On the basis of a critical survey of the literature up to this time on the effect of turbulence parameters on heat transfer on the flow around a sphere, there was confirmed:

—the possibility of the intensification of the process by the use of turbulence promoters;

—the lack of analytic and experimental methods, allowing for the synonymous evaluation of the effect of artificially induced turbulence;

—the lack of a synonymous opinion of the hitherto choice of corresponding parameters determining the effect mentioned.

2. There is confirmed the suitability of the simplex β proposed by Moscicka [91], considering as well the scale and the degree of turbulence for the interpretation of the data obtained in the result of the tests of the process of heat transfer for rotary bodies.

3. Interpretation of one's own experimental material (120 measurement points) by the use of simplex β allowed the formulating of the following criterial relationship:

$$Nu = 0.142Re^{0.6}Pr^{0.33}(\beta_d)^{-0.16}.$$

OZNACZENIA – SYMBOLS

d	– średnica kuli sphere diameter	m
$g(r)$	– współczynnik korelacji prędkości coefficient of correlation of velocity	
r	– promień radius	m
u, v	– składowe pulsacyjne w kierunku x, y fluctuating velocities in x, y direction	m/s
A_2, A_4	– stałe w rozwiązaniu GALLOWAYA [13] constants in GALLOWAY's solution [13]	
D_r^2	– wariancja resztkowa residual variance	
L	– całkowa skala burzliwości integral turbulence scale	m
$L_g = \frac{1}{R}\int_0^R g(r)dr$	– poprzeczna skala burzliwości transverse scale of turbulence	m
R	– promień tunelu powietrznego radius of air tunnel	m
R_y	– współczynnik korelacji correlation coefficient	
U, V	– uśredniona w czasie prędkość w kierunku x, y time-averaged velocity in x, y direction	m/s
	– współczynnik wnikania ciepła heat transfer coefficient	W/m²·deg
	– poziom istotności korelacji significance level of correlation	
	– stopień burzliwości intensity of turbulence	

LICZBY BEZWYMIAROWE – DIMENSIONLESS GROUPS

$Fs = (Nu-2)/Re^{0.5}Pr^{0.33}$	– liczba Frösslinga Frössling number
$Nu = \alpha d/\lambda$	– liczba Nusselta Nusselt number
$Pr = c\mu/\lambda$	– liczba Prandtla Prandtl number
$Re = Ud/\nu$	– liczba Reynoldsa Reynolds number
$Re_T = Re\varepsilon$	– burzliwa liczba Reynoldsa
$(\beta_R) = (L_g/R)\varepsilon^2$	– kryterium podobieństwa burzliwych pól przepływu wg [9] criterion of the similarity of turbulent flow fields after [9]
$(\beta_d) = (L_g/d)\varepsilon^2$	– kryterium podobieństwa burzliwych pól przepływu liczone względem średnicy kuli criterion of the similarity of turbulent flow fields calculated with respect to sphere diameter

INDEKSY – SUBSCRIPTS

$-$ – wartość średnia dla przekroju poprzecznego tunelu
average value for tunnel cross-section

i – w bezpośrednim sąsiedztwie warstwy granicznej
in immediate vicinity of boundary layer

∞ – w głównym strumieniu płynu
in the bulk of fluid

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